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## **Report Title**

Final Report: RF Control and Measurement of Superconducting Qubits

### **ABSTRACT**

This is the final report for the ARO/LPS project work at Yale University.

**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
12/30/2014 2.00	V. Manucharyan, M. H. Devoret, L. I. Glazman, Jens Koch. Charging Effects in the Inductively Shunted Josephson Junction, Physical Review Letters, (11 2009): 0. doi: 10.1103/PhysRevLett.103.217004
12/30/2014 3.00	V. E. Manucharyan, J. Koch, L. I. Glazman, M. H. Devoret. Fluxonium: Single Cooper-Pair Circuit Free of Charge Offsets, Science, (10 2009): 0. doi: 10.1126/science.1175552
12/30/2014 4.00	S M Girvin, M H Devoret, R J Schoelkopf. Circuit QED and engineering charge-based superconducting qubits, Physica Scripta, (12 2009): 0. doi: 10.1088/0031-8949/2009/T137/014012
12/30/2014 5.00	N. Bergeal, F. Schackert, M. Metcalfe, R. Vijay, V. E. Manucharyan, L. Frunzio, D. E. Prober, R. J. Schoelkopf, S. M. Girvin, M. H. Devoret. Phase-preserving amplification near the quantum limit with a Josephson ring modulator, Nature, (5 2010): 0. doi: 10.1038/nature09035
12/30/2014 6.00	M. D. Reed, B. R. Johnson, A. A. Houck, L. DiCarlo, J. M. Chow, D. I. Schuster, L. Frunzio, R. J. Schoelkopf. Fast reset and suppressing spontaneous emission of a superconducting qubit, Applied Physics Letters, ( 2010): 0. doi: 10.1063/1.3435463
12/30/2014 7.00	J. M. Chow, L. DiCarlo, J. M. Gambetta, A. Nunnenkamp, Lev S. Bishop, L. Frunzio, M. H. Devoret, S. M. Girvin, R. J. Schoelkopf. Detecting highly entangled states with a joint qubit readout, Physical Review A, (6 2010): 0. doi: 10.1103/PhysRevA.81.062325
12/30/2014 13.00	R. J. Schoelkopf, M. H. Devoret, Hanhee Paik, D. I. Schuster, Lev S. Bishop, G. Kirchmair, G. Catelani, A. P. Sears, B. R. Johnson, M. J. Reagor, L. Frunzio, L. I. Glazman, S. M. Girvin. Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture, Physical Review Letters, (12 2011): 0. doi: 10.1103/PhysRevLett.107.240501
12/30/2014 14.00	Nicholas A. Masluk, Ioan M. Pop, Archana Kamal, Zlatko K. Mineev, Michel H. Devoret. Microwave Characterization of Josephson Junction Arrays: Implementing a Low Loss Superinductance, Physical Review Letters, (9 2012): 0. doi: 10.1103/PhysRevLett.109.137002
12/30/2014 15.00	S. J. Weber, S. M. Girvin, I. Siddiqi, D. Zhou, K. W. Murch, U. Vool. Cavity-Assisted Quantum Bath Engineering, Physical Review Letters, (10 2012): 0. doi: 10.1103/PhysRevLett.109.183602
12/30/2014 16.00	K. W. Murch, E. Ginossar, S. J. Weber, R. Vijay, S. M. Girvin, I. Siddiqi. Quantum state sensitivity of an autoresonant superconducting circuit, Physical Review B, (12 2012): 0. doi: 10.1103/PhysRevB.86.220503
12/30/2014 17.00	Vladimir E. Manucharyan, Nicholas A. Masluk, Archana Kamal, Jens Koch, Leonid I. Glazman, Michel H. Devoret. Evidence for coherent quantum phase slips across a Josephson junction array, Physical Review B, (1 2012): 0. doi: 10.1103/PhysRevB.85.024521
12/30/2014 18.00	M. D. Reed, L. DiCarlo, S. E. Nigg, L. Sun, L. Frunzio, S. M. Girvin, R. J. Schoelkopf. Realization of three-qubit quantum error correction with superconducting circuits, Nature, (2 2012): 0. doi: 10.1038/nature10786

- 12/30/2014 19.00 John Clarke, Archana Kamal, Michel H. Devoret. Gain, directionality, and noise in microwave SQUID amplifiers: Input-output approach, *Physical Review B*, (10 2012): 0. doi: 10.1103/PhysRevB.86.144510
- 12/30/2014 20.00 K. Geerlings, S. Shankar, E. Edwards, L. Frunzio, R. J. Schoelkopf, M. H. Devoret. Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters, *Applied Physics Letters*, ( 2012): 0. doi: 10.1063/1.4710520
- 12/30/2014 8.00 F. Motzoi, L. Frunzio, S. M. Girvin, R. J. Schoelkopf, J. M. Chow, L. DiCarlo, J. M. Gambetta. Optimized driving of superconducting artificial atoms for improved single-qubit gates, *Physical Review A*, (10 2010): 0. doi: 10.1103/PhysRevA.82.040305
- 12/30/2014 9.00 M. D. Reed, L. DiCarlo, L. Sun, D. I. Schuster, L. Frunzio, R. J. Schoelkopf, B. R. Johnson. High-Fidelity Readout in Circuit Quantum Electrodynamics Using the Jaynes-Cummings Nonlinearity, *Physical Review Letters*, (10 2010): 0. doi: 10.1103/PhysRevLett.105.173601
- 12/30/2014 10.00 Baleegh Abdo, Flavius Schackert, Michael Hatridge, Chad Rigetti, Michel Devoret. Josephson amplifier for qubit readout, *Applied Physics Letters*, ( 2011): 0. doi: 10.1063/1.3653473
- 12/30/2014 11.00 Archana Kamal, John Clarke, M. H. Devoret. Noiseless non-reciprocity in a parametric active device, *Nature Physics*, (1 2011): 0. doi: 10.1038/nphys1893
- 12/30/2014 12.00 D. I. Schuster, Lev S. Bishop, I. L. Chuang, D. DeMille, R. J. Schoelkopf. Cavity QED in a molecular ion trap, *Physical Review A*, (1 2011): 0. doi: 10.1103/PhysRevA.83.012311
- 12/30/2014 21.00 Simon E. Nigg, Hanhee Paik, Brian Vlastakis, Gerhard Kirchmair, S. Shankar, Luigi Frunzio, M. H. Devoret, R. J. Schoelkopf, S. M. Girvin. Black-Box Superconducting Circuit Quantization, *Physical Review Letters*, (6 2012): 0. doi: 10.1103/PhysRevLett.108.240502
- 12/30/2014 22.00 Baleegh Abdo, Katrina Sliwa, Flavius Schackert, Nicolas Bergeal, Michael Hatridge, Luigi Frunzio, A. Douglas Stone, Michel Devoret. Full Coherent Frequency Conversion between Two Propagating Microwave Modes, *Physical Review Letters*, (4 2013): 0. doi: 10.1103/PhysRevLett.110.173902
- 12/30/2014 23.00 Flavius Schackert, Ananda Roy, Michael Hatridge, Michel H. Devoret, A. Douglas Stone. Three-Wave Mixing with Three Incoming Waves: Signal-Idler Coherent Attenuation and Gain Enhancement in a Parametric Amplifier, *Physical Review Letters*, (8 2013): 0. doi: 10.1103/PhysRevLett.111.073903
- 12/30/2014 24.00 Simon E. Nigg, S. M. Girvin. Stabilizer Quantum Error Correction Toolbox for Superconducting Qubits, *Physical Review Letters*, (6 2013): 0. doi: 10.1103/PhysRevLett.110.243604
- 12/30/2014 25.00 Baleegh Abdo, Katrina Sliwa, Luigi Frunzio, Michel Devoret. Directional Amplification with a Josephson Circuit, *Physical Review X*, (7 2013): 0. doi: 10.1103/PhysRevX.3.031001
- 12/30/2014 26.00 Zaki Leghtas, Gerhard Kirchmair, Brian Vlastakis, Robert J. Schoelkopf, Michel H. Devoret, Mazyar Mirrahimi. Hardware-Efficient Autonomous Quantum Memory Protection, *Physical Review Letters*, (9 2013): 0. doi: 10.1103/PhysRevLett.111.120501
- 12/30/2014 27.00 Zaki Leghtas, Gerhard Kirchmair, Brian Vlastakis, Michel Devoret, Robert Schoelkopf, Mazyar Mirrahimi. Deterministic protocol for mapping a qubit to coherent state superpositions in a cavity, *Physical Review A*, (4 2013): 0. doi: 10.1103/PhysRevA.87.042315
- 12/30/2014 28.00 B. Vlastakis, G. Kirchmair, Z. Leghtas, S. E. Nigg, L. Frunzio, S. M. Girvin, M. Mirrahimi, M. H. Devoret, R. J. Schoelkopf. Deterministically Encoding Quantum Information Using 100-Photon Schrodinger Cat States, *Science*, (09 2013): 0. doi: 10.1126/science.1243289

- 12/30/2014 29.00 Z. K. Mineev, I. M. Pop, M. H. Devoret. Planar superconducting whispering gallery mode resonators, *Applied Physics Letters*, ( 2013): 0. doi: 10.1063/1.4824201
- 12/30/2014 30.00 Baleegh Abdo, Archana Kamal, Michel Devoret. Nondegenerate three-wave mixing with the Josephson ring modulator, *Physical Review B*, (1 2013): 0. doi: 10.1103/PhysRevB.87.014508
- 12/30/2014 31.00 K. Geerlings, Z. Leghtas, I. Pop, S. Shankar, L. Frunzio, R. Schoelkopf, M. Mirrahimi, M. Devoret. Demonstrating a Driven Reset Protocol for a Superconducting Qubit, *Physical Review Letters*, (3 2013): 0. doi: 10.1103/PhysRevLett.110.120501
- 12/30/2014 32.00 S. Shankar, M. Hatridge, Z. Leghtas, K. M. Sliwa, A. Narla, U. Vool, S. M. Girvin, L. Frunzio, M. Mirrahimi, M. H. Devoret. Autonomously stabilized entanglement between two superconducting quantum bits, *Nature*, (11 2013): 0. doi: 10.1038/nature12802
- 12/30/2014 33.00 M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K. M. Sliwa, B. Abdo, L. Frunzio, S. M. Girvin, R. J. Schoelkopf, M. H. Devoret. Quantum Back-Action of an Individual Variable-Strength Measurement, *Science*, (01 2013): 0. doi: 10.1126/science.1226897
- 12/30/2014 34.00 M. H. Devoret, R. J. Schoelkopf. Superconducting Circuits for Quantum Information: An Outlook, *Science*, (03 2013): 0. doi: 10.1126/science.1231930
- 12/30/2014 35.00 Gerhard Kirchmair, Brian Vlastakis, Zaki Leghtas, Simon E. Nigg, Hanhee Paik, Eran Ginossar, Mazyar Mirrahimi, Luigi Frunzio, S. M. Girvin, R. J. Schoelkopf. Observation of quantum state collapse and revival due to the single-photon Kerr effect, *Nature*, (3 2013): 0. doi: 10.1038/nature11902
- 12/30/2014 36.00 Ioan M. Pop, Kurtis Geerlings, Gianluigi Catelani, Robert J. Schoelkopf, Leonid I. Glazman, Michel H. Devoret. Coherent suppression of electromagnetic dissipation due to superconducting quasiparticles, *Nature*, (4 2014): 0. doi: 10.1038/nature13017
- 12/30/2014 37.00 Baleegh Abdo, Katrina Sliwa, S. Shankar, Michael Hatridge, Luigi Frunzio, Robert Schoelkopf, Michel Devoret. Josephson Directional Amplifier for Quantum Measurement of Superconducting Circuits, *Physical Review Letters*, (4 2014): 0. doi: 10.1103/PhysRevLett.112.167701
- 12/30/2014 38.00 Mazyar Mirrahimi, Zaki Leghtas, Victor V Albert, Steven Touzard, Robert J Schoelkopf, Liang Jiang, Michel H Devoret. Dynamically protected cat-qubits: a new paradigm for universal quantum computation, *New Journal of Physics*, (04 2014): 0. doi: 10.1088/1367-2630/16/4/045014
- 12/30/2014 39.00 L. Sun, A. Petrenko, Z. Leghtas, B. Vlastakis, G. Kirchmair, K. M. Sliwa, A. Narla, M. Hatridge, S. Shankar, J. Blumoff, L. Frunzio, M. Mirrahimi, M. H. Devoret, R. J. Schoelkopf. Tracking photon jumps with repeated quantum non-demolition parity measurements, *Nature*, (7 2014): 0. doi: 10.1038/nature13436
- 12/30/2014 40.00 R. J. Schoelkopf, U. Vool, I. M. Pop, K. Sliwa, B. Abdo, C. Wang, T. Brecht, Y. Y. Gao, S. Shankar, M. Hatridge, G. Catelani, M. Mirrahimi, L. Frunzio, L. I. Glazman, M. H. Devoret. Non-Poissonian Quantum Jumps of a Fluxonium Qubit due to Quasiparticle Excitations, *Physical Review Letters*, (12 2014): 0. doi: 10.1103/PhysRevLett.113.247001
- 12/30/2014 41.00 C. Wang, Y. Y. Gao, I. M. Pop, U. Vool, C. Axline, T. Brecht, R. W. Heeres, L. Frunzio, M. H. Devoret, G. Catelani, L. I. Glazman, R. J. Schoelkopf. Measurement and control of quasiparticle dynamics in a superconducting qubit, *Nature Communications*, (12 2014): 0. doi: 10.1038/ncomms6836

**TOTAL: 40**

Number of Papers published in peer-reviewed journals:

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

Received      Paper

**TOTAL:**

Number of Papers published in non peer-reviewed journals:

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**(c) Presentations**

Number of Presentations: 0.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received      Paper

**TOTAL:**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received      Paper

**TOTAL:**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
06/03/2010	1.00 L. DiCarlo, M. Reed, L. Sun, B. Johnson, J. Chow, J. Gambetta, L. Frunzio, S. Girvin, M. Devoret, R. Schoelkopf. Preparation and Measurement of Three-Qubit Entanglement in a Superconducting Circuit, (09 2010)
<b>TOTAL:</b>	<b>1</b>

Number of Manuscripts:

Books

<u>Received</u>	<u>Book</u>
<b>TOTAL:</b>	

<u>Received</u>	<u>Book Chapter</u>
<b>TOTAL:</b>	

Patents Submitted

- 1) Error-Corrected Quantum Registers for a Modular Superconducting Quantum Computer (61/754,298, 61/871,061, ~~PCT/US2014/012080 , PCT/Us2014/012073~~)
- 2) Josephson Directional Amplifier (61/891, 226, PCT/US14/60694)
- 3) Wireless Josephson Bifurcation Amplifier (61/943,150)

Patents Awarded



## Awards

Robert Schoelkopf:

John Stewart Bell Prize, 2013 (with M. Devoret)

Fritz London Memorial Prize, 2014 (with M. Devoret and J. Martinis)

Max Planck Forschungspreis (Max Planck Research Award), 2014

M. Devoret:

John Stewart Bell Prize, 2013 (with R. Schoelkopf)

Fritz London Memorial Prize, 2014 (with R. Schoelkopf and J. Martinis)

Matthew Reed (PhD Student at Yale, graduated 2013):

CGS/Proquest Distinguished Dissertation Award, 2014

APS Richard Greene Award for experimental condensed matter physics, 2014

## Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Matthew Reed	1.00	
Adam Sears	0.50	
Nick Masluk	0.50	
Archana Kamal	0.50	
Yehan Liu	1.00	
Flavius Schackert	0.50	
Teresa Brecht	1.00	
Ananda Roy	1.00	
Jacob Blumoff	0.50	
Philip Reinhold	0.50	
Vladimir Manucharyan	0.50	
Kyle Serniak	0.70	
Uri Vool	0.70	
Evan Zalys	0.70	
Zlatko Minev	1.00	
Katrina Sliwa	0.30	
Clarke Smith	1.00	
Luke Burkhart	1.00	
<b>FTE Equivalent:</b>	<b>12.90</b>	
<b>Total Number:</b>	<b>18</b>	

## Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Baleegh Abdo	0.70
Ioan Pop	0.30
Nissim Ofek	0.50
Zaki Leghtas	0.50
Leo DiCarlo	0.30
Chen Wang	1.00
<b>FTE Equivalent:</b>	<b>3.30</b>
<b>Total Number:</b>	<b>6</b>

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### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Luigi Frunzio	0.50	
Mazyar Mirrahi	0.50	
Michel Devoret	0.20	
Robert Schoelkopf	0.20	
Steve Girvin	0.20	Yes
<b>FTE Equivalent:</b>	<b>1.60</b>	
<b>Total Number:</b>	<b>5</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: .....

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense .....

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: .....

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### Names of Personnel receiving masters degrees

<u>NAME</u>
<b>Total Number:</b>

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### Names of personnel receiving PHDs

<u>NAME</u>	
Adam Sears	
Archana Kamal	
Flavius Schackert	
Nick Masluk	
Vladimir Manucharyan	
Matthew Reed	
<b>Total Number:</b>	<b>6</b>

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### Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

---

### Sub Contractors (DD882)

### Inventions (DD882)

### Scientific Progress

This is the final report for the ARO/LPS project at Yale University, on the RF control and measurements of superconducting qubits. During this project, we performed the proposed research work, which was revolving around four major axes: I. The improvement of qubit coherence by investigating the nature of the various sources of decoherence, II. The improvement of readout fidelity by establishing the parameters influencing the efficiency and speed, III. The novel manipulation and entanglement of multiple qubits by developing gate hardware, protocols and room temperature electronics extendable to systems comprising more than two qubits, and IV. The development of a scalable architecture combining superconducting linear resonators and superconducting qubit. The overall goal of the project was to assess the potential of superconducting qubits for the construction of a quantum computer based on superconducting Josephson circuits.

By project end, we have realized qubit and cavity devices with an energy decay times in excess of a millisecond, or an improvement by almost three orders of magnitude. Using novel degenerate and non-degenerate amplifiers developed during this project, we can now perform the readout of qubits with a fidelity and speed allowing more than 2000 bits to be learned on the qubit evolution during its lifetime. New protocols and hardware have been tested successfully that entangle three qubits, entangle a qubit and a cavity, entangle a qubit and a flying coherent state, prepare a Schroedinger state in a cavity, stabilize autonomously the ground state of one qubit or an entangled state of two qubits. The error correction of a three-qubit register was also shown. Basing ourselves on the knowledge stemming from these various measurements, we are now able to propose an original architecture that, with minimum hardware, can implement fault-tolerant memory and gates on logical qubits. In all, more than 50 publications in peer-reviewed journals were generated in this project (the list is given at the end of the report, with a majority of the publications in rank A international journals such as Nature, Science and Physical Review Letters; in the following, we refer to this list by numbers in square brackets).

These results, especially improved “3D” designs and parametric amplifier readout chains, have been widely adopted and successfully reproduced by many groups across the superconducting qubit community. Through the program, we have provided an existence proof that superconducting qubits satisfying the quantum error correction threshold are possible with existing materials, fabrication techniques, and existing room-temperature electronics, leading to a growing belief that large-scale quantum computation with solid-state devices will eventually be realized [13].

### Technology Transfer

# **RF Control and Measurement of Superconducting Qubits**

Final Report for ARO Grant to Yale University

Grant number: W911NF-09-1-0514



Michel Devoret

Luigi Frunzio

Steven Girvin

Leonid Glazman

Robert Schoelkopf

Yale University

Departments of Applied Physics and Physics

2/14/2015

**Period of performance**  
**September 15<sup>th</sup> 2009 - September 15<sup>th</sup>, 2013**

**Report Abstract:**

This is the final report for the ARO/LPS project at Yale University, on the RF control and measurements of superconducting qubits. During this project, we performed the proposed research work, which was revolving around four major axes: I. The improvement of qubit coherence by investigating the nature of the various sources of decoherence, II. The improvement of readout fidelity by establishing the parameters influencing the efficiency and speed, III. The novel manipulation and entanglement of multiple qubits by developing gate hardware, protocols and room temperature electronics extendable to systems comprising more than two qubits, and IV. The development of a scalable architecture combining superconducting linear resonators and superconducting qubit. The overall goal of the project was to assess the potential of superconducting qubits for the construction of a quantum computer based on superconducting Josephson circuits.

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## Project overall goals and team composition:

This ARO/LPS project was constructed to be a comprehensive theoretical and experimental investigation of the limitations of coherence, control and readout of superconducting qubits such as the transmon, the fluxonium. The project was also supposed to investigate the same issues on microwave cavity resonators which are necessary companions of the artificial atoms of circuit QED systems. The project also specified that the results should lead, during the project duration, to the generation a new architecture which, while taking into account the limitations discovered in the other research line of the project, would exploit the strength of superconducting solid-state devices to evaluate their ultimate potential as a quantum technology.

The project was a collaboration between the theoretical group of Prof. Steve Girvin and two experimental groups (Prof. Robert Schoelkopf and Prof. Michel Devoret, as assisted by senior research scientist Luigi Frunzio), all located at Yale University. In each group, several teams worked on the project, each team typically consisting of a post-doc working with one or two graduate students. We also systematically collaborated with the theoretical group of Prof. Leonid Glazman at Yale University.

## Questions that defined the workflow of the project:

The workflow of the project was based on the concept that we would implement in a superconducting circuit system the following quantum optics paradigm: several artificial atoms are coupled to resonators that can serve two purposes: coupling the atoms and reading their state. As we are going to see in this report, the results obtained by the project made it evolve in a direction that will be extremely fruitful for the development of quantum solid state technology: some resonators, with particular high quality factor, can be used to store quantum information, and the role of the atoms is shifted from quantum memory and the target of gates to that of serving the resonator by endowing it with the right amount of non-linearity.

In any case, in the entire scope of the project, the effective Hamiltonian at the heart of all the systems addressed by theory and experiments is supposed to be as close as possible to

$$\frac{H}{\hbar} = \sum_{j=1}^{N_a} \sum_{s=e,f,h..} \omega_j^s |j,s\rangle \langle j,s| + \sum_{i=1}^{N_r} \omega_i a_i^\dagger a_i + \sum_{i,j,s} \chi_{ijs} |j,s\rangle \langle j,s| a_i^\dagger a_i \quad (1)$$

where the first term contains the Hamiltonians of the artificial atoms, the second term contains the Hamiltonians of the resonators, and the third term describes the coupling between the atoms and the resonators. In these expressions, the indices  $i, j, s$  refer to the resonator index, the atom index and the state of one particular atoms, respectively. Atomic states run g, e, f, h, ... etc... using a notation often used in atomic physics. The symbol  $a$  denotes the resonator boson field operator, and  $\omega_i$  denotes the frequency of a particular excitation. Finally, the 3-index parameter  $\chi_{ijs}$  describes the particular frequency shift that a cavity undergoes due to a particular atom being in a certain state. This parameter corresponds to the crucial effect of circuit QED: the effect that allows the readout of a particular atomic state by the observation of the phase shift that a flying coherent state undergoes when it visits a resonator coupled to the relevant atom. In our project, the number of atoms  $N_a$  went up to 3 and the number of resonators  $N_r$  went up to 2.

Thus, given to the open nature of our system, one must consider, in addition to this Hamiltonian, several extra ingredients: i) the atoms can be driven by oscillating fields  $h_j$  that bring them from the ground state to any excited state, and the cavity can be excited in coherent states by drives  $\varepsilon_j$ .

ii) the resonators are on purpose coupled to external transmission lines, inducing a finite inverse lifetime  $\kappa_i$  for the photons. This inverse lifetime determines the speed at which one can extract information from a resonator.

Given this ideal effective Hamiltonian, and the driven-damped character of our circuits, a certain number of questions were considered during the project.

### Qubit and resonator coherence problem

First, the states of the atoms have inverse lifetimes  $\Gamma_j^s$  due to decoherence mechanisms. In turn, each decoherence mechanisms can act on the atoms by dephasing them or by provoking their energy to decay, or both. Thus for the transition involving the ground and first excited state (qubit 0 to qubit 1) we have the inverse coherence time

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

where  $T_1$  denotes the energy relaxation time (inverse energy loss rate) and  $T_\phi$  denotes the dephasing time. At the outset of the project, the question was to determine which of the known or suspected sources of loss and dephasing were actually most important, to then pinpoint their location or the materials defects in which they originated, and then to design and fabricate devices with improved characteristics and materials so as to increase the coherence time. The work of this project thus complemented and ran parallel to the CSQ project whose main goal was to identify materials problems in superconducting qubits. While much remains to be understood in the identification of the mechanisms, we will see in this report that, without any change to the materials used in qubit fabrication, we have been able to increase the coherence time by several orders of magnitude simply by designing qubits that were less exposed to known losses. We will discuss our method, based on the analysis of participation ratios of various components to the energy of an excitation (whether it is an atom-like or resonator-like excitation), below in this report.

Second, the resonators themselves can have imperfections. They can have internal dissipation and their quality factor  $Q$  must thus be decomposed into

$$\frac{1}{Q} = \frac{1}{Q_{ext}} + \frac{1}{Q_{int}}$$

where, for a particular resonator  $i$

$$\kappa_i = \frac{\omega_i}{Q_{i,ext}}$$

Here also, mechanisms had to be investigated by the participation method to determine which energy loss mechanism was dominant. Great progress was obtained by designing 3D resonators instead of planar ones. The reasoning is simple: in a 3D geometry, the dielectric can be made dominantly the vacuum, a trustworthy insulator. Removing the influence of lossy dielectrics,

inherent in all planar circuits, was a key step in determining other residual mechanisms. By allowing 3D designs, the importance of interfaces and surface imperfections was also substantially improved. All superconducting quantum circuits, regardless of their design, are inherently three-dimensional devices, which must be respected when building and using them. Our understanding generated during the period of this grant indicates that 3D devices will always allow a substantial (several order of magnitude) increase in coherence for a given set of materials properties.

Third, spurious electromagnetic modes, not accounted for in the Hamiltonian (1), can spuriously couple to the atoms or the resonators. Their own losses can then be inherited by the parts of the systems. The question addressed by the project was to find methods that would remove all possible spurious electromagnetic modes, to both prevent ambiguity in the study of the losses of key elements, and improve the general microwave hygiene of our circuits.

Fourth, the effective Hamiltonian does not include possible higher order coupling terms between the atoms and the readout resonator. Thus it is possible that the qubit loses energy to the readout resonator. This type of non-QNDness of the system is called the Purcell effect, and the project addressed the question of its minimization. This problem was dealt with use of Purcell filters in the case of the Transmon. The fluxonium possesses a natural robustness to the Purcell effect by the nature of the matrix elements coupling the atom to the readout resonator.

#### The readout problem

In dispersive type of readout described above is performed by sending a microwave pulse containing a few photons to the readout resonator and measuring the phase shift (typically of the order of 1 radian) induced by the state of the atom. The duration of the pulse is a few resonator lifetime (of the order of 100ns). The question is thus to amplify this signal with a minimum amount of noise. At the start of the project, we had decided to use Josephson parametric amplifiers. The question addressed by the project was how to design and realize optimal amplifiers in terms of their bandwidth, gain, added noise and dynamic range. These desired characteristics tend to be mutually incompatible and finding the best compromise was the task tackled by the project, both theoretically and experimentally. In addition, it is important in the future that the amplifier is integrated with the qubit. However present day circulators and isolators that prevent further amplifier stages on the route to room temperature acquisition electronics then to send their noise back to the quantum circuits. It was thus desirable to investigate how to perform directional functions with only Josephson elements.

#### The gate synthesis problem

While in principle Hamiltonian (1) supplemented by drives of the qubits and resonators allows arbitrary manipulations of quantum states of the system, the question addressed by the project was to determine the simplest protocols that would, in a minimum amount of time, perform a quantum information processing function. Or in other words, what is the optimal sequence of signals that need to be sent to the qubits and resonators? Of particular interest were the operations that would entangle the qubits and perform quantum error corrections.



### The scaling architecture problem

Even if the different components of the architecture outlined by Hamiltonian (1) were separately optimized, the question would remain as to whether it is possible to assemble a large set of qubits, resonators, and corresponding readout chains in a way that would be scalable, i.e. the complexity, measured in number  $N_q$  of qubits, should render the cost and difficulty of realization grow no faster than the first power of  $N_q$  and possibly less. On the technical side, we addressed the question of simplification of the room temperature electronics. On the theory and experimental side, the question we addressed was whether we could take advantage of the large Hilbert space offered by superconducting cavities and their relatively large quality factors to encode quantum information in hardware-efficient way, with the Josephson artificial atoms serving to provide non-linearity to the cavity, instead of serving as the quantum memory. In such architecture, there is a leverage of the quality of the atoms. For instance, if the quality factor of the cavity is 10 million while the qubit is only a million, it is possible to transfer enough non-linearity from the qubit to the cavity without having the qubit participating on more than 10% of the cavity. This causes the spoiling the quality factor by only a factor of two, making the combined qubit+cavity system having a quality factor 5 times better than the qubit alone. The exploration of this strategy, together with the exploration of FPGA electronics, constituted our main effort in devising a scaling strategy for quantum circuit architecture.

### **Methodologies, devices and concepts elaborated and/or employed during the project**

#### Participation ratios [35, 34 15, 8]:

The overall quality factor  $Q$  of a circuit element of a resonator (inductance or capacitance), defined as the ratio between the maximum energy stored in that element, and the energy lost per radian of phase increase due to all the dissipation mechanisms of that element can be written as

$$\frac{1}{Q} = \sum_m \frac{p_m}{Q_m}; \quad \sum_m p_m = 1$$

Here,  $p_m$  denotes the particular participation of dissipation mechanism  $m$  and  $Q_m$  stands for the quality factor associated with the mechanism (it would be the overall quality factor if the mechanism would fully participate). By measuring the overall quality factor of a resonator and by knowing the participation of a suspected mechanism, one can get a lower bound on the quality factor of that mechanism, assuming it is the only contributor. The reason why only a lower bound can be obtained is that the contribution of other dissipation mechanisms can mask the influence of the mechanism under investigation. It is thus of extreme importance to reduce first the trivial sources of dissipations, for instance energy lost to spurious modes, that can be cured by improved microwave design of the experiment. Furthermore, by varying the participation ratio of the suspected dissipation mechanism (for instance the participation of the dissipation at the surface of the substrate can be diminished by varying the pitch between two conductors placed on the substrate and whose potentials oscillate in phase), one can infer from the measurement of the overall quality factor a better assessment of the quality factor associated with that mechanism. But the challenge then is that one has to make sure that in changing the participation ratio of the target, everything else had stayed the same in the experiment.

### Compact resonators [34]

These resonators are made by combining a distributed meander inductor and a distributed inter-digitated capacitor in the most compact manner as possible, in order to benefit from a ratio of about 4-5 between on one hand the lowest resonating mode of the structure, which can be described as an oscillation of energy flowing back and forth between the inductor-like part and the capacitor-like part (LC-type resonant mode), and on the other hand the self-resonances of each of the reactive parts. It is possible to design these resonators so as to vary the independently the participation of capacitive losses and inductive losses. Results were consistent with the presence of surface capacitive losses.

### 3D Transmon [35]

Preliminary experiments having pointed out the importance of capacitive losses originating at the surface of the substrate, we designed a novel type of transmon, nicknamed 3D transmon, in which the participation of this type of dielectric loss was minimized. Instead of a very miniaturized compact interdigitated capacitance shunting the junction, a large antenna fulfills this role, with the effect of distributing the electric field over a much large volume, minimizing the participation of the substrate surface. The direct radiation losses of this antenna are eliminated by placing the chip supporting the junction and antenna in a 3D cavity. Resorting to a 3D cavity is not abandoning the miniature aspect of the superconducting qubits. The cavity is in fact the sample box itself, which has to be present in any case to shield the qubits from spurious infrared radiation. One should rather view the 3D-transmon strategy as a way to fight decoherence by getting rid of all superfluous and suspicious hardware in the sample box: ground planes on the chip, wire bonds, printed circuit board for the connections between chip and transmission lines couplers. The strategy can be described better by pointing out to the fact that the coupling between transmission lines, the resonator and the qubit is now done only through miniature microwave antennas. Such elements can be much better characterized at microwave frequencies than miniature wire connections and ground planes with many cuts. Let us point also the fact that the mode structure of a 2D chip becomes extremely complicated when the chip is placed in a metallic enclosure. The 3D strategy makes the enclosure part of the system and maximizes the use of vacuum as the dominant dielectric.

### Black box quantization [23]

Once it is accepted that the quantum circuit is formed by the reunion of various electromagnetic distributed elements combined with Josephson junctions, a key problem arises as to best formulate the Hamiltonian of the system. We have developed a partly phenomenological methodology for this purpose, which we have nicknamed "Black-Box Quantization (BBQ)". In this methodology, the junction is decomposed into its linear inductance, given by the Josephson inductance  $L_J$ , and a non-linear parallel inductance in which the phase of the junction is treated to 4th order. Using a Maxwell equation solver like HFSS, the electromagnetic eigenmodes of the linear system incorporating the junction only through  $L_J$  are then found. The BBQ scheme then produces all the Kerr and cross-Kerr terms of the Hamiltonian from the participation ratios of all the modes in the junction phase fluctuations.

#### Purcell filters [58,14]

The transmon poses the following problem: given a readout cavity coupled to a transmission line with a rate  $\kappa$ , the Purcell relaxation rate  $\Gamma_1$  of the transmon with self- Kerr non-linearity  $\alpha$  and cross-Kerr  $\chi$  to the cavity is intrinsically linked to  $\kappa$  by the relation:

$$\Gamma_1 = \chi \frac{\kappa}{\alpha}$$

This limits the signal-to-noise ratio of the readout-out since the length of the readout signal cannot exceed a certain number of cavity lifetimes. However, this limitation can be circumvented if behind the readout cavity, in the transmission line linking it to the first stage of amplification a filter is inserted that is reflective at the qubit frequency while passing the readout signal bandwidth at the cavity frequency. We have successfully explored this strategy.

#### Superinductor and bridge-free fabrication techniques [51, 50, 28]

Analysis of the full fluxonium Hamiltonian revealed that its superinductor – an array of large Josephson junction producing a large kinetic inductance – needed to be as large as possible while maximizing the plasma frequencies of the arrays and the Josephson energy of each individual junctions. Progress in the superinductor characteristics were made possible through a new fabrication technique developed previously in Grenoble by one of our post-docs. The microwave quality factor of superinductors were characterized by incorporating them in a resonant circuit.

#### Inductive readout and 3D Fluxonium [28,6,2]

The analysis of the T1 limitations of the fluxonium showed that any on-chip capacitance in parallel with the phase-slip junction was detrimental. The capacitance involved in the coupling to the readout resonator could be eliminated by coupling the artificial atom inductively. Furthermore the readout resonator itself could be realized in the form of a resonant antenna. This led to the concept of the 3D fluxonium in which both the qubit and its readout resonator are integrated in the artificial superconducting atom, itself placed on sapphire chip in the middle of a 3D cavity. Unlike the 3D transmon, the atom is not part circuit, part cavity. The atom is entirely located on-chip, the cavity providing only one convenient way to interrogate the readout resonator. The cavity can be replaced by a waveguide which offers the possibility of multiple atom readout.

#### Josephson junction with double bias: phase-bias at dc and voltage-bias at RF [38,36]

The usual description of the Josephson effect involves either a voltage-bias of the junction or a phase bias. With any of these biases, the 4th term in the Josephson theory of the current flowing across a junction is quite unclear. We have progressed in the understanding of the original prediction by considering a junction that is phase-biased at DC and voltage-biased at RF frequency. This form of bias is ideally suited to the qualitative understanding of the role of out-of-equilibrium quasiparticles in the decoherence of both the fluxonium and transmon.

#### Trilinear coupling of modes [48,47, 18,16,12]

The Josephson ring modulator offers the advantage to couple together three resonators by an Hamiltonian term that is linear in each of the resonator field amplitudes. This offers a robust way to process analog quantum signal by decoupling completely the signal and idler channels

from the pump. This non-degenerate mode of operation is particularly important for frequency converter operations.

#### Hanger geometry for multiplexing of signals to different resonators [34,15]

The coupling of a transmission line to an electromagnetic resonator can be done in three different ways: reflection, transmission and hanger. The hanger type of coupling allows a single line to service a large number of resonators, as for example in photon detectors based on MKID's. We have used this technique to compare resonators of different geometries.

#### Cat-codes[4]

A new concept generated by this project has involved Schroedinger cat states which are a coherent superposition of two coherent states:

$$\begin{aligned} |\text{re. even cat}\rangle &= \frac{1}{\sqrt{2}} |\alpha\rangle + |-\alpha\rangle ; & |\text{im. even cat}\rangle &= \frac{1}{\sqrt{2}} |i\alpha\rangle + |-i\alpha\rangle \\ |\text{re. odd cat}\rangle &= \frac{1}{\sqrt{2}} |\alpha\rangle - |-\alpha\rangle ; & |\text{im. odd cat}\rangle &= \frac{1}{\sqrt{2}} |i\alpha\rangle - |-i\alpha\rangle \end{aligned}$$

A qubit can be encoded using the 2 even cat states. When those would decay to the odd states, the error would not harm the superposition but could be detected by measuring the number of photons in the cavity.

### **Overview of main results:**

#### Coherence of 3D Transmon [35]

This new artificial atom that brought a ten-fold increase in the coherence of superconducting qubits promoted the idea of microwave hygiene by giving a convincing demonstration that avoiding the spurious lossy modes in 2D systems can greatly help overcome coherence limitations of quantum circuits. It also provided supporting evidence for the idea that surface dielectric loss plays a role in the relaxation of the qubit. Finally it also brought a bound on excess quasiparticle numbers in transmons.

#### Energy relaxation time of 3D Fluxonium [6,2]

The relaxation time of the transmon can be increased by another factor of ten by going to the fluxonium qubit, which minimizes the participation of the substrate capacitance at the expense of exposing the qubit more to quasiparticle dissipation. This qubit, together with the Cooper pair box demonstrated that the dielectric losses of the intrinsic capacitance of the junction are less than that of the substrate. It also showed that the excess quasiparticle number in an island is of order of unity. Finally, being based on of order one hundred junctions that have to work perfectly; it shows that arrays of junctions can successfully be employed in superconducting quantum circuits. Its peak in relaxation time at half-flux-quantum demonstrates the validity of the 4th term in the Josephson current formula, an effect untested since the original prediction of the effect in 1962.

#### Dynamics of quasiparticles [24, 2,1]

Experiments on the transmon and fluxonium have determined that coherence of superconducting qubits were influenced by excess quasiparticles, and that the number of quasiparticles fluctuates with time on long time scales. Quasiparticles are spontaneously generated, trapped and can recombine. The rates corresponding to these processes have been measured and it has been shown that vortices trapped in the film of the qubit play an important role in the trapping of quasiparticle. The trapping power of a single vortex has been measured.

#### Photon shot noise [25]

One key mechanism influencing the dephasing of all superconducting qubits was identified theoretically and experimentally: fluctuations in the number of photons in the readout cavity dephase the qubit and it is of utmost importance to minimize the number of photons in ALL modes having dispersive shifts with the qubits.

#### Long-lived cavities for single microwave photons [15, 8]

Important progress has been made in the coherence time of superconducting resonators at the single photon levels with quarter wavelength post 3D cavities, where the coherence time is now 10ms, thanks in great part to the seamless character of the cavity. Surface treatment of the aluminum, as well as its purity, has also been found a key factor. Another route in which the participation ratio of the resonant mode in the seams is minimized has also been explored, that of whispering galleries realized by a parallel plate resonator in the form of two closed rings. We have nicknamed this architecture 2.5D as it borrows both from vacuum-as-insulator aspect of 3D and the integrated fabrication techniques of 2D. Results with this new type of resonator easily surpass that of integrated 2D cavities but can still serve to characterize the quality of metallic thin films.

#### Entanglement of 3 qubits: GHZ and error correction via repetition code [43,22]

The goal of manipulating the maximally entangled state of a register of 3 qubits is a necessary step in the road to the understanding of error correction mechanisms. We have generated the GHZ state of 3 qubits and performed the error correction protocol corresponding to the repetition code.

#### Controlling the state of a resonator [21,20,10, 9,43]

We have demonstrated that we can map the state of a qubit onto the state of a resonator. This so-called QCMAP protocol is a crucial operation for the implementation of cat-codes. In the same direction we have demonstrated that we could create a Schroedinger cat containing of order one hundred quantum of action, setting a new record on the macroscopicity of a quantum state. Of utmost important in the development of cat-codes, jumps of the parity of the number of photons in a cavity have been observed, which demonstrated that the error syndrome can be monitored continuously.

#### Entangling state of qubit with a flying coherent state [14]

Measuring a quantum system can randomly perturb its state. The strength and nature of this back-action depend on the quantity that is measured. In a partial measurement performed by an ideal apparatus, quantum physics predicts that the system remains in a pure state whose evolution can be tracked perfectly from the measurement record. We demonstrated this property

using a superconducting qubit dispersively coupled to a cavity traversed by a microwave signal. The back-action on the qubit state of a single measurement of both signal quadratures was observed and shown to produce a stochastic operation whose action is determined by the measurement result. This accurate monitoring of a qubit state is an essential prerequisite for measurement-based feedback control of quantum systems. Alternatively, one can describe the results of these measurements as a demonstration of the entanglement of a qubit with a flying coherent pulse.

#### High-speed and high-efficiency readout[39,18]

We have pioneered at Yale the use of Josephson amplifiers for the readout of qubits. In this round of funding, we have perfected non-degenerate amplifiers, for which the pump tone is incommensurate with the readout frequency, to achieve the best fidelity, efficiency and measurement speed. We also have addressed the issue of dynamical range which will be important in the future to speed up the readout.

#### Autonomous state stabilization[19, 7]

Stabilization of a quantum state by feedback can be done in two different manners: through measurements and a correction loop involving an external information processing system at room temperature or by realizing a combination of drive and dissipation that stabilizes the state autonomously. This last way is also called reservoir engineering or autonomous feedback, as it can be shown that the dissipative, non-linear nature of the system can be viewed as producing a conditional evolution. We have realized such protocols to demonstrate not only the dynamical cooling of a qubit to its ground state, but also the stabilization of a Bell state of two qubits sitting in the same cavity. The two qubits do not interact directly, but the dissipative interaction of their joint parity with the reservoir that consists of the readout cavity transmission line, together with appropriate Rabi drives of the qubit, maintains the entanglement of the two qubits for an arbitrary duration.

#### Directionality of readout amplifier chain[37, 33, 11,5]

Using Josephson parametric amplifiers for QND measurements of qubit has imposed itself as the technique obtaining the best fidelity, efficiency and measurement speed. However these parametric devices are used in reflexion and also do not protect the measured system from backaction originating higher up in the amplification chain. Thus, nonreciprocal devices, such as circulators and isolators, are required in these measurements both to separate input from output and to protect the quantum system from unwanted classical backaction. We have realized a microwave quantum-limited amplifier that is directional and can therefore function without the front circulator needed in many quantum measurements. The amplification takes place in only one direction between the input and output ports. Directionality is achieved by multipump parametric amplification combined with wave interference. We have verified the device noise performances by using it to read out a superconducting qubit and observed quantum jumps. With an improved version of this device, the qubit and preamplifier could be integrated on the same chip.

**The 43 published peer-reviewed articles from the research done under the project:**

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### **Yale PhD theses resulting from the research done under the project:**

1. Jerry Chow
2. Kurtis Geerlings
3. Blake Johnson
4. Archana Kamal
5. Vladimir Manucharyan
6. Nick Masluk
7. Matt Reed
8. Adam Sears